

# **Oceanography of the Indonesian Seas**

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## **LONG-TERM GOALS**

The Indonesian Throughflow (ITF) is central to the ocean and atmosphere heat and freshwater budgets and sea surface temperature (SST) patterns of the Pacific and Indian Oceans. Oceanographers and climatologists are keenly interested in determining not just the mean ITF, but also its variability at annual and interannual scales, and its resultant heat and freshwater fluxes. Models suggest significant interannual variability in the ITF, though they have difficulty in simulating the specific sources and magnitude of the throughflow within the complex bathymetry of the Indonesian seas and channels. My long-term goal is to provide a solid observation-based understanding of the ITF.

## **OBJECTIVES**

The objectives of the Arlindo Project, a joint oceanographic research endeavor of Indonesia and the United States are: to define the magnitude and variations of the ITF mass, heat and freshwater fluxes and relate these to large scale data fields; to improve our understanding of the ITF sources waters and of the mixing processes that alter the stratification enroute through the Indonesian Seas.

## **APPROACH**

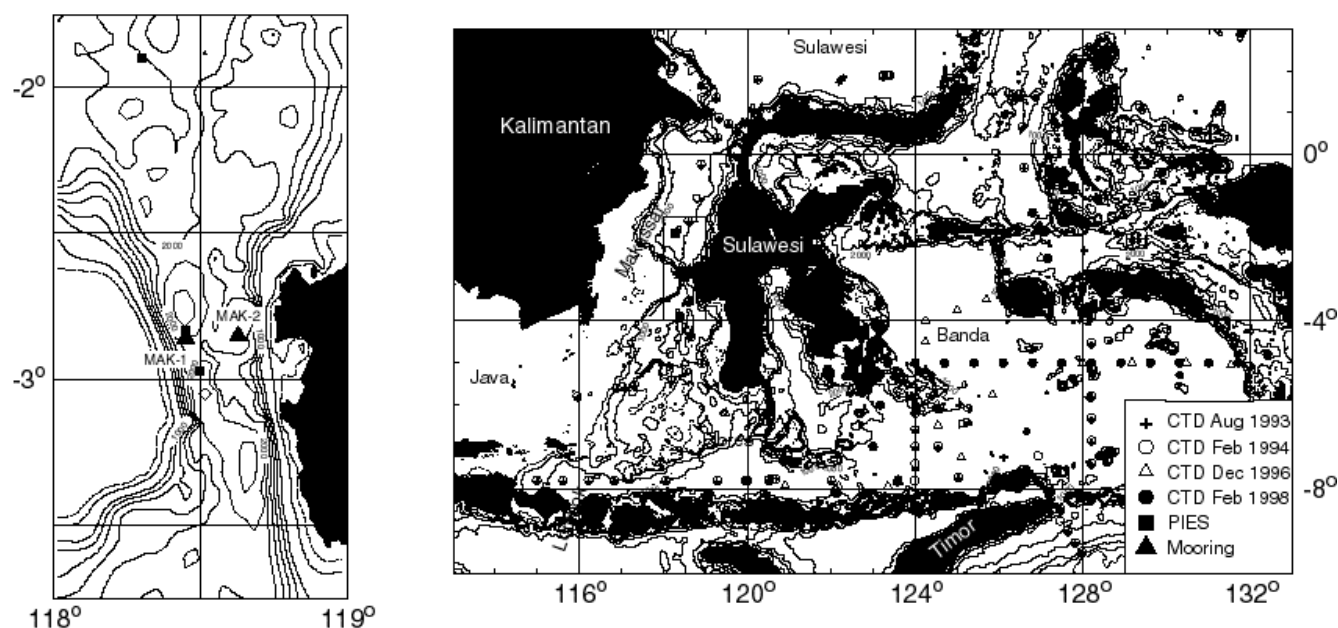
Time series of *in situ* and satellite-derived data are used to study the mean and variable form of the Indonesian throughflow. Two moorings (Dec 1996-July 1998) provide the information on the throughflow within Makassar Strait. Collection of CTD stations since 1991 enable quantitative description of the throughflow pathways, water mass sources and their variability. Satellite data used is primarily altimetric data. Regional VOS XBT data collection programs provide views of the thermal structure of the thermocline, which we find are closely linked to ITF mass flux. Comparison of the Indonesian interior seas data to the varied data sets collected in the Lesser Sunda Islands and in the Australian-Indonesian Bight as well as ocean scale data sets is carried out.

## **WORK COMPLETED**

Velocity and temperature were measured at various depths within Makassar Strait as part of the Indonesian-US Arlindo program (Fig 1.) This was accomplished at two moorings, MAK-1 (23 November 1996 to 8 July 1998) and MAK-2 (1 December 1996 to 21 February 1998), deployed near 3°S within the Labani Channel, a 2000 m deep, 45 km wide constriction in Makassar Strait. West of the Labani channel is a <10 m deep coral reef rimming a broad promontory of generally less than 30 m depth, confining the throughflow to the Labani channel. Along channel currents (Fig 2) and transport

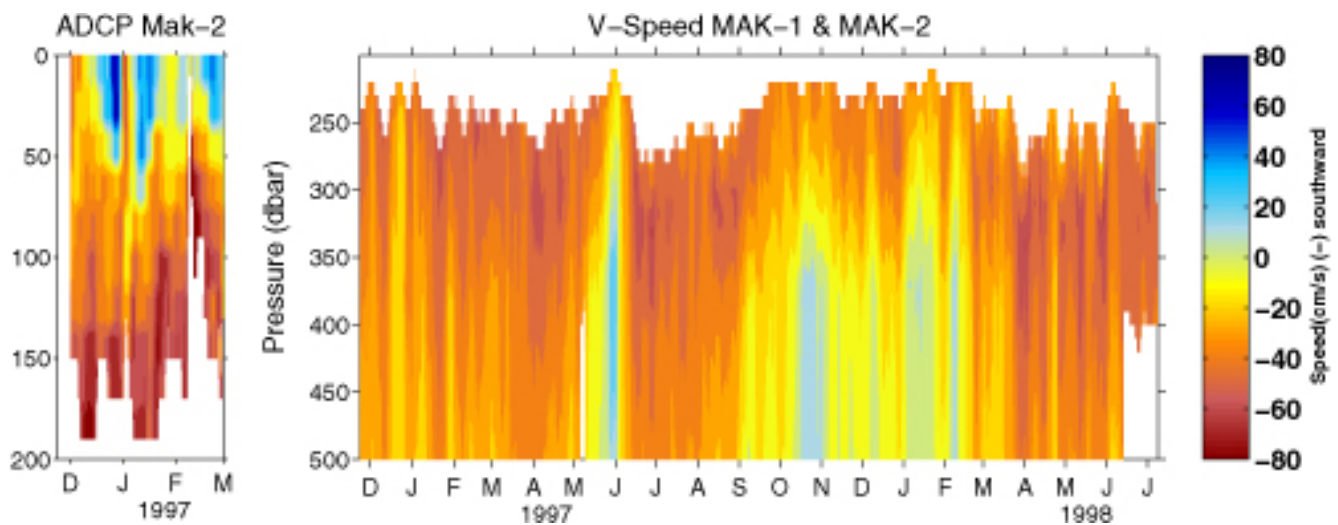
(Fig 3) estimates for Makassar Strait are based on the time series records from Aanderaa current meters on each mooring, set at depths of 200, 250, 350, 750 and 1500 db (for zero wire angle; the 1500 db instrument was only on MAK-1). Each mooring had an upward looking ADCP at 150 m, but only a partial record at MAK-2 was recovered. Temperature and pressure sensors were attached to the mooring line.

In 1998 the CTD station distribution was greatly enhanced by collection of data in the eastern Banda Sea.

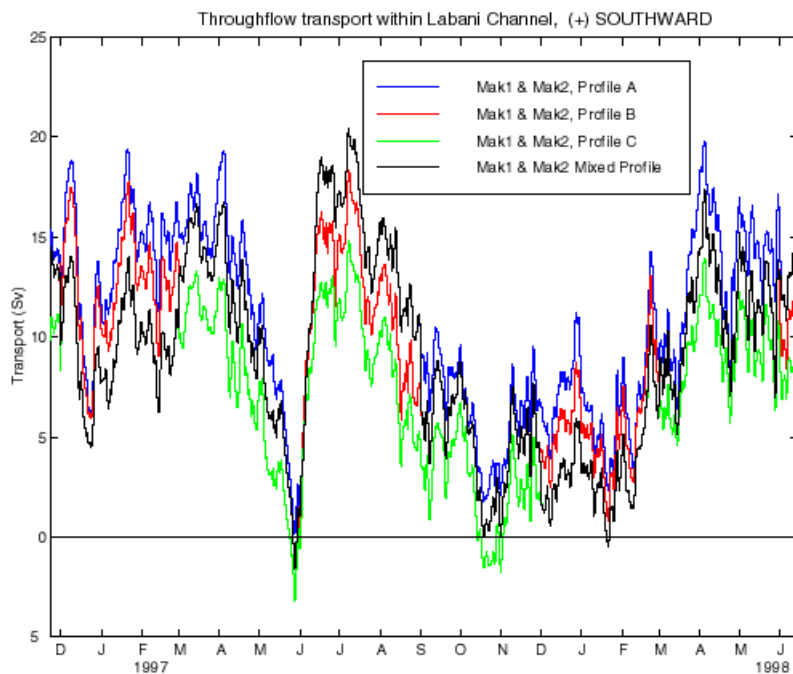


**Figure 1.** The position (triangles) of the 1996-98 moorings in Makassar Strait, MAK-1 ( $2^{\circ}52'S$ ,  $118^{\circ}27'E$ ) and MAK-2 ( $2^{\circ}51'S$ ;  $118^{\circ}38'E$ ). Position of bottom pressure and inverted echo sounders sensors (PIES) are shown by the solid box symbols. Arlindo CTD stations obtained from 1993 to 1998 are shown by solid circles.

A graduate student (K. Vranes) supported under an associated Aasert grant (N00014-97-1-0722) is working on calculating an estimate of energy transport in the Makassar Strait using MAK-1 observations. He has constructed a time series of energy transport from the surface to 600m (approx. sill depth) using MAK-1 speeds and temps, t-pod temps, NCEP sst's. In interpolating speeds from the top-most Aanderaa to the surface, the profile scheme set out by Gordon et al., (1999b) has been followed. The 'best' estimate of energy transport is slightly less than model predictions.



**Figure 2.** The 2 day low pass filtered along channel (orientation of  $170^\circ$ ) speed at MAK 1 and MAK 2 Aanderaa current meters and for the three month record of the MAK-2 upwards looking ADCP.



**Figure 3.** Throughflow transport based on 1 week low pass filter values within Makassar Strait, for the four speed versus depth model profiles described in Gordon et al. 1999b. Data from both moorings are used to the end of the MAK-2 record in February 1998, after which only the MAK-1 data is used. The throughflow transport towards the Indian Ocean, towards the south, is displayed as positive values.

## RESULTS

Velocity and temperature were measured at various depths within Makassar Strait as part of the Indonesian-US Arlindo program (Gordon et al. 1998). This was accomplished at two moorings, MAK-1 (23 November 1996 to 8 July 1998) and MAK-2 (1 December 1996 to 21 February 1998), deployed near 3°S within the Labani Channel, a 2000 meter deep, 45 km wide constriction in Makassar Strait. The mooring observations span the entire cycle of the strong 1997/1998 El Niño. The 1997 average throughflow is 9.3 Sv, with a range of about  $\pm 2.5$  Sv depending on how the surface flow is taken into account (Gordon and Susanto, 1999; Gordon et al., 1999). The results show that throughflow within Makassar Strait can account for all of the Pacific to Indian interocean transport.

A high correlation ( $r = 0.73$ ) is found between Makassar transport and ENSO, though as with the temperature data, the time series is far too short to say this with assurance. Most of the remaining variance is explained by the annual cycle, with a June maximum and December minimum. A strong intra-seasonal event occurs from late May to July 1997, which appears to be due to the arrival of a semi-annual Kelvin wave from the Indian Ocean (Sprintall et al. submitted to JGR).

A high correlation ( $r = 0.67$ ) is found between variability in the average thermocline temperature (Ffield et al. submitted to GRL), and variability in the southward Makassar volume transport. During high (low) volume transport, the average temperature of the thermocline is also high (low). In addition, during the measurement period, the Makassar thermocline temperature is highly correlated ( $r = -0.87$ ) to NINO3. This reveals that the Makassar temperature field - when coupled with the throughflow - transmits the equatorial Pacific El Niño and La Niña temperature fluctuations into the Indian Ocean. In 1997, the internal energy transport was 0.5 PW, lower than model estimates; during La Niña the internal energy transport is expected to be higher.

The findings of the Arlindo CTD data show that the western throughflow route (Makassar Strait) is always composed of North Pacific thermocline and intermediate water, though with varied strength of the water mass core values. The eastern routes are a mixture of North and South Pacific water, the latter dominating the lower thermocline and deep water. The South Pacific presence is stronger during the winter monsoon (Jan-Feb) than in the summer monsoon. For a few regions it is possible to construct a time series of Arlindo CTD and CFC stations collected 1991. These data suggest that during La Niña periods, which coincide with higher throughflow transport, North Pacific water has a greater presence in the thermocline of the eastern seas. This supports the premise that the ENSO mirrors the monsoon phase in terms of water mass representation within the throughflow: El Niño is 'like' the winter monsoon.

A zonal CTD section across the Banda Sea obtained in 1998 reveals a large clock-wise gyre, which advects waters including excess freshwater from the Flores Sea to the northern Banda Sea, and then into the eastern Banda Sea southward flow. A clock-wise gyre was identified in earlier Arlindo CTD observations, but the gyre in 1998 encompassed the full Banda Sea. The water mass view of the throughflow is emerging: Makassar transport with the Java Sea freshwater export enters the Banda, as a river flows into a large lake. It mixes vertically and laterally with some salt addition from South Pacific thermocline, the blend passes southward in the eastern Banda Sea to enter the Timor passages and Indian Ocean. Does variability of Makassar throughflow pass into the Banda and eventually into the Indian Ocean? Or does the Banda act as a capacitor, smoothing out the higher frequency variability?

## **IMPACT/APPLICATIONS**

The Makassar mass, heat and freshwater fluxes obtained from the mooring data are important in evaluating the varied models of the throughflow, which until now have been poorly constrained with *in situ* observation (Gordon and McClean, 1999; Wajsowicz et al., submitted to JPO; Burnett et al, submitted to GRL)). At least in preliminary view, the seasonal and interannual variability of Makassar transport seems to be very different from that seen in models, or the in the indirect or partial observation made within the Timor Sea. The Arlindo CTD and CFC data set with the mooring temperature record data will lead to a better understanding of the advective and mixing processes that shape the thermohaline stratification of the Indonesian Seas.

## **TRANSITIONS**

The Arlindo products are of use in the development of regional and global ocean circulation models: Julie McClean (NPS), Vladimir Kamenkovich (USM), Roxana Wajsowicz (U Maryland) and Raghuram Murtugudde (NASA/GSFC) are all engaged in considering the impact on models of the Arlindo observations. There are also non-US transitions, mainly the joint analysis of the Arlindo and JADE (French-Indonesian) program, which measured Timor Sea transports at the time of the MAK moorings, and with Gary Meyers who is monitoring the thermal field from Java to Australia.

## **RELATED PROJECTS**

The Arlindo Research is funded mainly by NSF (ends in Feb 2000), which also funds the Arlindo Indonesian research of Amy Ffield (temperature pods) and Rana Fine (CFCs) of Rosenstiel School for Marine and Atmospheric Science. The Arlindo PIES research of Silvia Garzoli (NOAA/AOML) is funded by ONR. Remote sensing research is supported by NASA: Chet Koblinsky at the Goddard Space Flight Center. Janet Sprintall (Scripps Institution of Oceanography) has an array of shallow pressure sensors in the Lesser Sunda Islands, to monitor the time variability of the throughflow outflow in the Timor Sea as seen in the sea surface slope.

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